Soft Magnets to Achieve High-Efficiency Electric Drive Motors of Exceptional Power Density

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Project ID: elt234

Overview

Timeline

- Start: October 1, 2019
- End: September 30, 2021
- Percent complete: 20%

Budget

- Total project funding
  - $450 K (Federal)
  - $0 K (Cost share)
- Funding for FY 2019: $150K

Barriers and targets

- Barriers addressed
  - Magnet cost and rare-earth element price volatility
  - Non-rare-earth electric motor performance
- Targets
  - 33 kW/l at $6/kW with 8x reduction in volume

Partners

- Oak Ridge National Laboratory
- National Renewable Energy Laboratory
- Sandia National Laboratory

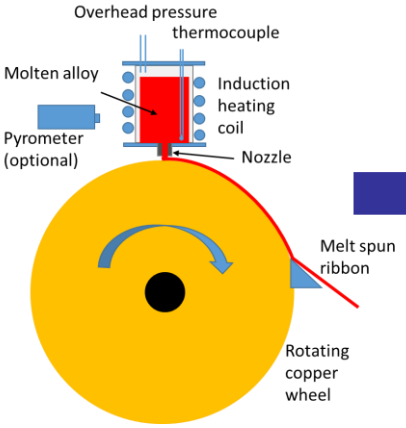
OAK RIDGE National Laboratory

NREL NATIONAL RENEWABLE ENERGY LABORATORY

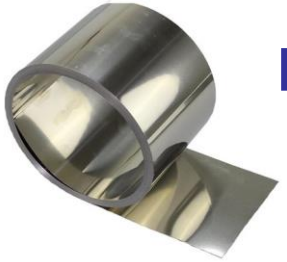
Sandia National Laboratories

Relevance

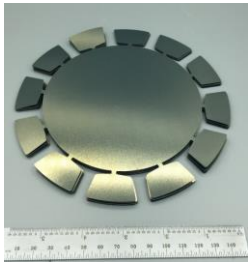
- Objective
  - Develop soft magnetic materials suitable for electric motors with exceptionally high power density
- Impact
  - Reduces iron loss at higher frequency to maintain efficiency
  - Improve motor power density
  - Maintain system cost-effectiveness



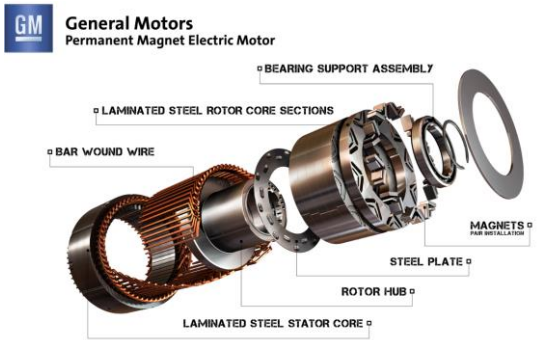
Continuous and ductile Fe-6.5%Si ribbon



Improved mechanical property for laminates preparation.



Motor with High Bs, low Iron loss Fe-6.5%Si motor laminates.



Reference: https://gm-volt.com/2011/10/28/gm-shows-off-electric-motors-for-spark-ev-and-more/

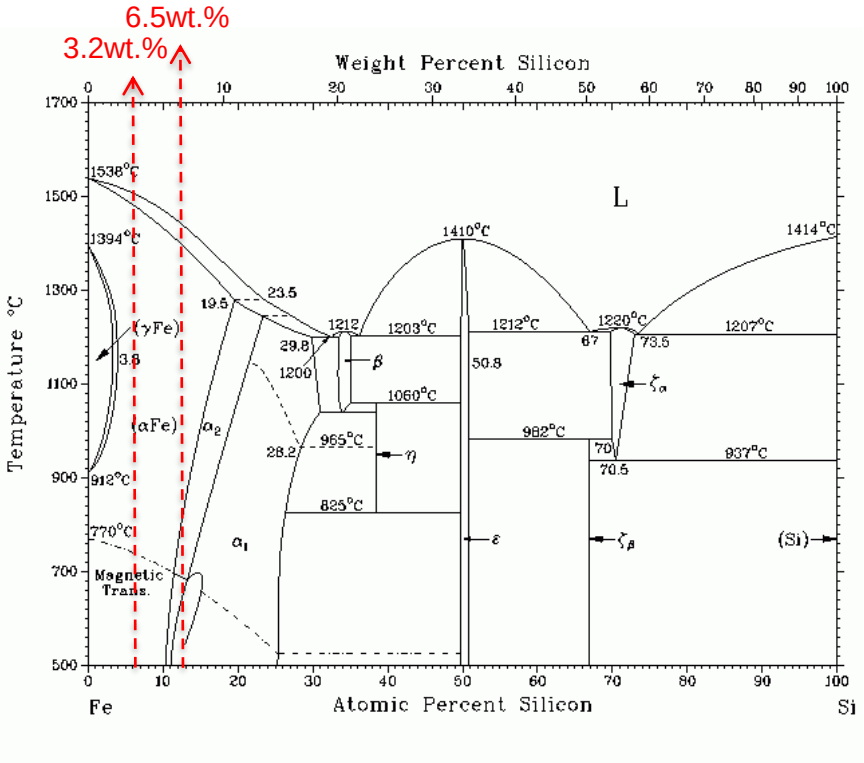
Milestones

Tasks #	Description	2019				
	Soft Magnets to Achieve High-Efficiency Electric Drive Motors of Exceptional Power Density	1	2	3	4	Status
Yr1-Q1	Establish crucible design for adaptable sheet forming in new melt spinning system.					50%
Yr1-Q2	Initial demonstration of the planar flow casting system with a model alloy.					100%
Yr1-Q3	Demonstrate planar flow casting of 6.5% Si steel sheet with 25 mm width					
Yr1-Q4	Characterization of the fabricated sheet (microstructure, electrical and magnetic properties)					

Challenges (6.5% Si Steel)

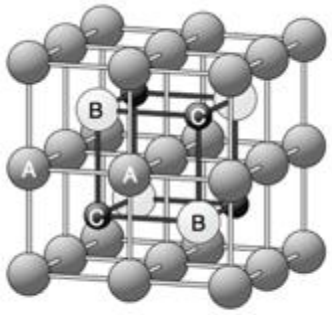
Advantages of 6.5% Si Steel

FeSi steels	Ms (T)	DC relative permeability	Electric resistivity (μΩ-cm)	Magnet ostrictio n (ppm)	Core loss $W_{10/400}$ (W/kg)
3.2% Si	1.96	18,000	52	7.8	14.4
6.5% Si	1.80	23,000	82	0.1	5.7



Challenges of 6.5% Si Steel

Too brittle to be manufactured using conventional hot/cold-roll processes



α- FeSi	A2	All sites are randomly occupied by Fe or Si
$α_2$- FeSi	B2	C, B sites are randomly occupied by Fe or Si
$α_1$- FeSi	$D0_3$	C sites are randomly occupied by Fe or Si

Approach (6.5%Si Steel)

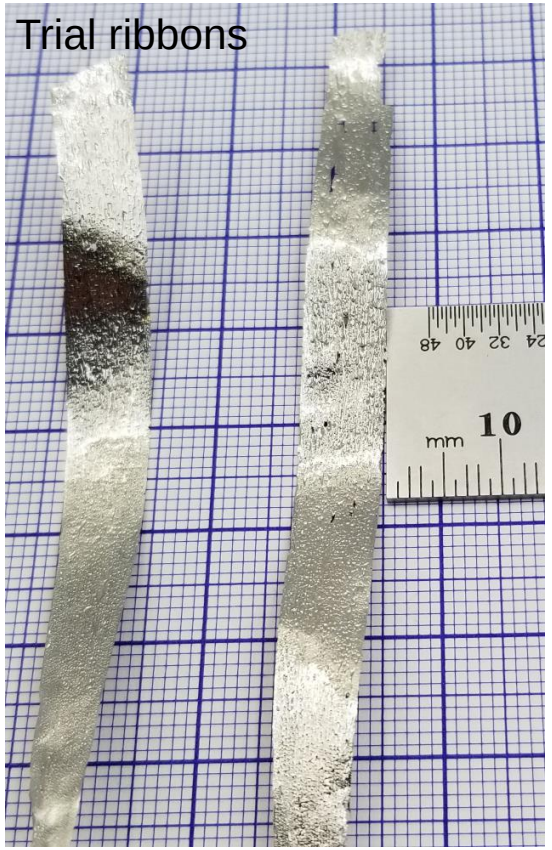
- Rapid solidification suppresses deleterious ordering phases
  - Use the planar flow casting technique to produce wide and thin ductile sheet suitable for motor stator and rotor applications.
- Optimize sheet hardness for high speed stamping process
  - Post casting annealing

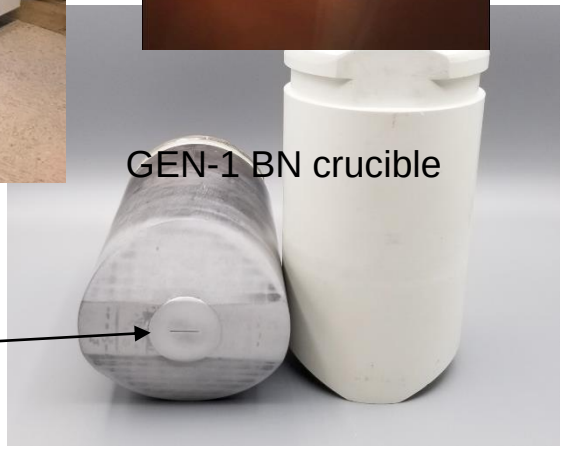
	Planned milestones and annual go/no-goes
2019	• Demonstrate the wide (>25 mm) rapidly solidified 6.5%Si steel sheet is viable for motor applications
2020	• Develop laminate material/insulation and stamping/stacking process for 6.5%Si steel sheet

1) G. Ouyang, X. Chen, Y. Liang, C. Macziweski, J. Cui, A review of Fe-6.5%Si alloy – a promising soft magnetic material for sub-kHz application. *Journal of Magnetism and Magnetic Materials*. 2019 July; 481: 234-250.
2) S. Cui, G. Ouyang, T. Ma, C. Macziewski, L. Zhou, M. Kramer, V. Levitas, J. Cui, Thermodynamic and kinetic analysis of the melt spinning process of Fe-6.5 wt.% Si alloy. *Journal of Alloys and Compounds*. 2019 January; 771: 643-648.
3) G. Ouyang, B. Jensen, W. Tang, K. Dennis, C. Macziewski, S. Thimmaiah, Y. Liang, J. Cui, Effect of wheel speed on magnetic and mechanical properties of melt spun Fe-6.5 wt.% Si high silicon steel. *AIP Advances*. 2018 May; 8(5): 056111.
4) J. Tangudu, G. Ouyang, J. Cui, Trade Studies for a Manganese Bismuth based Surface Permanent Magnet Machine. 2018 IEEE Transportation Electrification Conference and Expo (ITEC), Long beach, CA. 2018 June; 600-05.

Technical Accomplishments

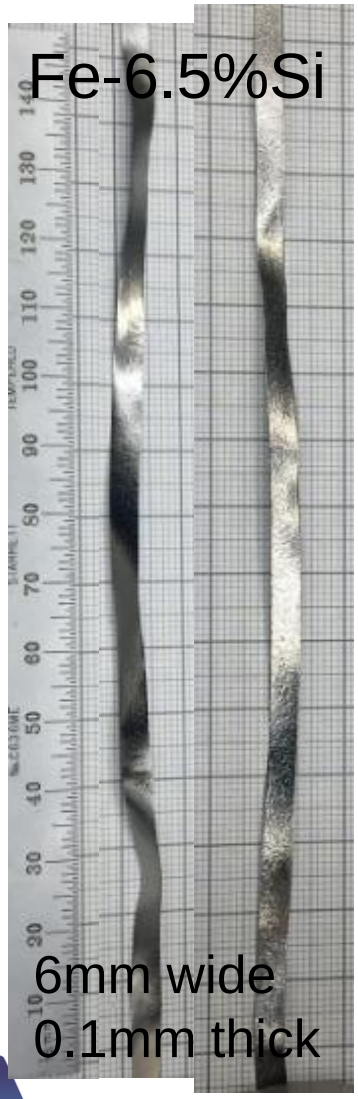
Melt-spinner (0.5 kg capacity)



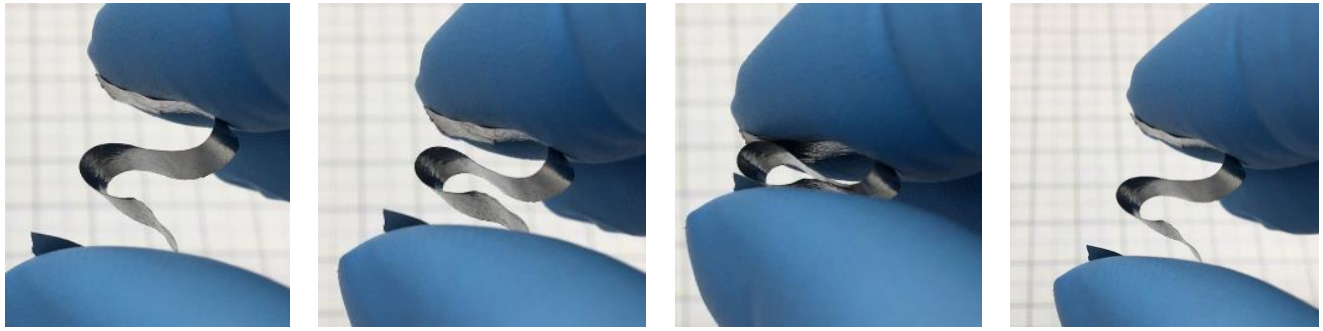


10 mm wide continuous ribbons using a model alloy (FeSiB)

Technical Accomplishments



The ribbon is highly ductile



Time lapse of a video

As spun ribbon can be wound into a core for magnetic testing.

- Consistently producing 6 mm wide 0.1mm thick Fe-6.5%Si ribbons using small melt spinner.
- As spun ribbon has low Iron loss of 12.3 W/kg at 400Hz 1T.

Responses to Previous Year Reviewers' Comments

- N/A (this is the first first review).

Collaboration and Coordination

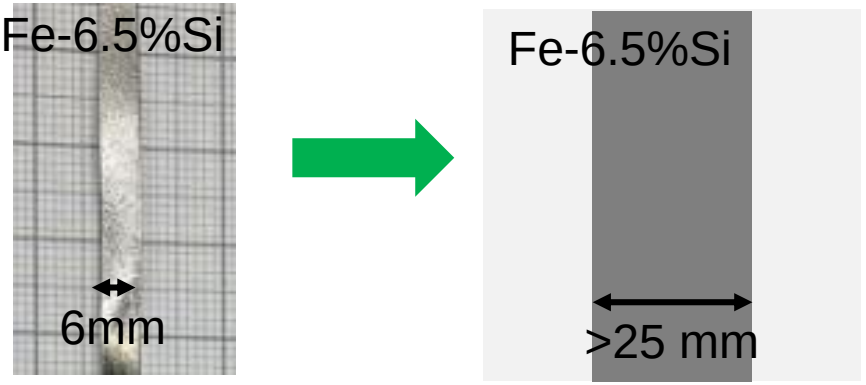
- Magnetic structure characterization of FeSi steel
- System level performance

- Thermal mechanical properties

- Nano-synthesis of soft magnetics for high frequency application

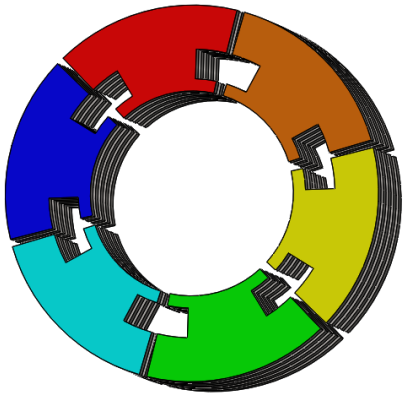
Remaining Challenges and Barriers

- Ribbon production
  - Width
  - Thickness
  - Surface finish
  - Processability



0.03m to 0.1mm thick

- Effective use of materials for making stators
  - Modular design
- Composition optimization
  - Manufacturability
  - Performance
    - Core losses
    - Increase induction



Modular laminate teeth

Proposed Future Research

Key Challenges

- Demonstration of scalability for industry adoption.
- Optimizing core loses while maintaining manufacturability
  Casting at such high temperature requires advanced cooling technology for copper wheel.

Future work

- Improve coating, stamping and stacking of thin laminates.
  - ✓ Scalability
  - ✓ Cost

Verify material manufacturability by coin ring punch test

Perfect Fe – 6.5 wt.% Si produced by large melt spinner

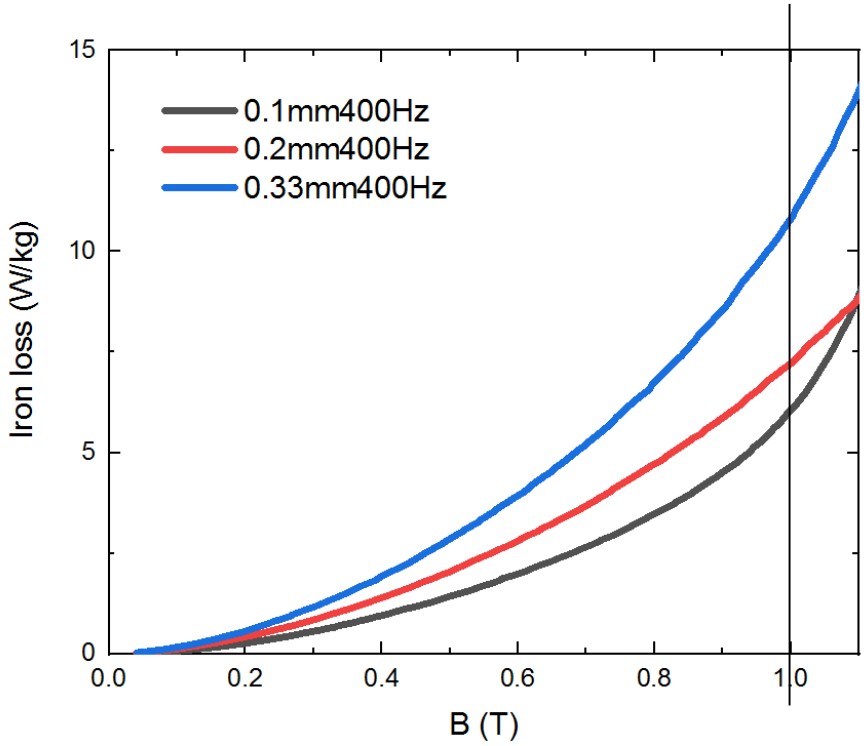
Any proposed future work is subject to change based on funding levels.

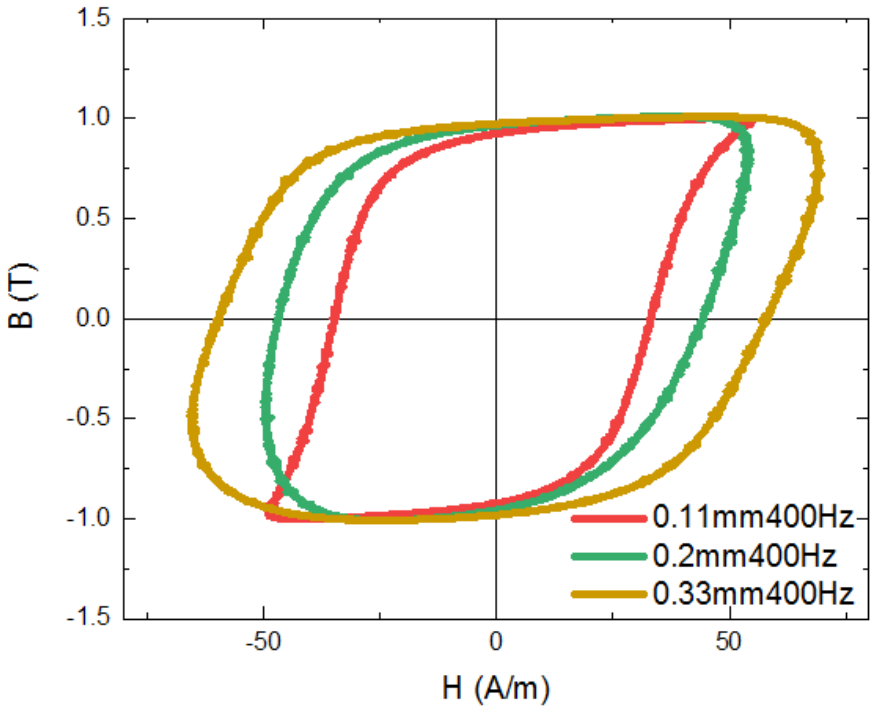
Summary

- Modifying traditional planar flow casting methods to simultaneously achieve disordered phase with larger grain size for the 6.5% Si steel.
  - Reduce core losses yet maintain formability
- Demonstrated planar flow casting system with model alloy
  - continuous ribbons with 10 mm width were obtained.
- Developing 25 mm wide ribbon of 6.5% Si steel
  - Melting point is ~300 ℃ higher than the model alloy

Technical Backup Slides

Choice of ribbon thickness





- Core loss increase with frequency and thickness
- Thinner sample has lower Eddy current loss but higher hysteresis losses
- For low iron loss at 400Hz at high inductor (~1T), and easy of manufacturing, 0.1mm ribbon is desirable.